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Citation for published version:
Calvert, J 2013, 'Engineering biology and society: reflections on synthetic biology', *Science Technology and Society*, vol. 18, no. 3, pp. 405-420.

Published In:
Science Technology and Society

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Published as: Calvert, J (2013) 'Engineering biology and society: reflections on synthetic biology' *Science, Technology & Society* 18 (3): 405-420

Abstract
Synthetic biology, according to some definitions, is the attempt to make biology into an engineering discipline. I ask what is meant by this objective, which seems to have excited and energised many people and encouraged them to start working in the field. I show how synthetic biologists make a point of distinguishing their work from previous genetic 'engineering', which is described as bespoke and artisan. I examine synthetic biologists' accounts of the differences between biology and engineering, which often oppose comprehension to construction. I argue that synthetic biology, like other branches of engineering, aims to meet recognised needs, and to make the world more manipulable and controllable. But there are tensions within the field; some synthetic biologists have reservations about the extent to which biology can be engineered, and ask whether it is necessary to develop a new type of engineering when working with living systems. After exploring these debates, I turn to some of the broader consequences of making biology easier to engineer, particularly the deskilling and democratisation of the technology. I end by arguing that because synthetic biologists are skilled at bringing together both technical and social forces, they are appropriately described as 'heterogeneous engineers'.

Keywords
Synthetic biology, engineering, heterogeneous engineers, design, tinkering

Introduction
As someone who has previously studied science and scientists, it is fascinating to become involved in a field where there are many engineers. Synthetic biology is attractive to engineers, particularly because of the explicit attempt to make biology into an engineering discipline that we see in the dominant approaches to the field. This involvement of engineers leads to lively discussions among synthetic biologists about the nature of engineering, and how it differs from science, and how an engineer's approach to living systems might be different from a biologist's. In this paper I attempt to elucidate these discussions by drawing on literature which deals with engineering, such as Vincenti's (1990) classic work, and research in science and technology studies. I ask to what extent ideas about engineering knowledge – its ameliorative impulses and its drive for mastery and control – can be said to apply to synthetic biology. I then examine the attempts to apply engineering principles to synthetic biology, focusing particularly on modularity and decoupling. My discussion of modularity shows how contested the concept is, even in the context of conventional forms of engineering. It also shows how moves towards modularising or 'blackboxing' biological systems have enabled new communities to become involved in synthetic biology. My discussion of decoupling leads me to consider the central role of design in engineering, and how the introduction of design inevitably opens up synthetic biology to political and economic considerations. I then move on to look at the specificities of the biological substrate, which, some maintain, demand a *new* type of engineering, one that differs qualitatively from the engineering of inanimate

substances. I ask whether in the context of biology we should replace our idea of an engineer with that of a 'tinkerer', who is arguably better adapted to deal with the contingencies and specificities of the natural world (Jacob 1977). Efforts are being made to train engineers to work with these noisy, unpredictable biological systems, however, and something that is particularly interesting about this training is that it often incorporates social and ethical concerns. I link this discussion to Law and Callon's (1988) notion of 'heterogeneous engineers', which applies particularly well to synthetic biologists because of their skill in orchestrating social, political and technical factors. Finally I consider some of the consequences for the future of the application of the (rather narrow) engineering imagination to biology, and how this might be challenged by the entry of new global communities into field.

This paper draws on several years of participant observation in the emerging field of synthetic biology at a range of different conferences, workshops and meetings in the UK, the US and Asia. Detailed records have been kept throughout of my observations, conversations, interactions and reflections. Synthetic biologists are only quoted here by name when I refer to a comment made in a public meeting; otherwise they are quoted by anonymised code name. I also draw on the scientific literature in synthetic biology.

Synthetic biology

One of the immediately striking features of synthetic biology is that there is a great deal of discussion about what is and what is not synthetic biology, with competing definitions and border disputes. A simple initial way of grasping the field is to distinguish between three schools of synthetic biology, which focus on biological entities of increasing scale (see O'Malley et al. 2008): the construction of standardized biological parts (normally made of DNA, and often analogised to Lego bricks); the synthesis of whole genomes, including Craig Venter's recent work (see Gibson et al. 2010); and the creation of simple 'proto' cells. My main interest in this paper is in the parts-based or 'BioBrick' approach, and the definition of synthetic biology from this perspective is 'the design and construction of new biological parts, devices, and systems and the re-design of existing, natural biological systems for useful purposes'.[1]

One of the most important and conceptually interesting aspirations of this approach is to make biology into an engineering discipline. We can see this trend in the titles of many survey articles on the field, such as 'Synthetic biology: new engineering rules for an emerging discipline' (Adrianantanandro et al. 2006), and 'A partnership between biology and engineering' (Brent 2004). In this paper I ask: what is meant by this objective, which seems to have excited and energised many people and encouraged them to start working in the field? What assumptions underlie it? And what consequences does it have?

Although I primarily focus on one approach to synthetic biology, it is important to say something about how the other branches fit into the engineering vision. Synthetic biologists working on whole genomes or protocells do not usually describe themselves as doing engineering, but they do share the engineer's aspiration to reduce complexity in their synthetic biological constructs. Scientists working on protocells, for example, say that they want to understand how every bit of their artificial cell operates.[2] For this reason, some protocell researchers argue that their approach is a more authentic expression of engineering than the BioBricks approach, because it aims for absolute control.

Synthetic biologists who do embrace the engineering vision make a point of distinguishing their work from previous so-called genetic 'engineering', since they think that 'Genetic engineering doesn't look or feel like any form of engineering' (Endy quoted in De Vriend 2006). The distinction between synthetic biology and genetic engineering is put nicely by a UK synthetic biologist: 'The engineering equivalent of genetic engineering is to get a bunch of concrete and steel, throw it into a river, and if you can walk across, call it a bridge'.[3] He adds that for this reason 'genetic engineering can be considered more of an artisan craft than an engineering discipline' (Elfick 2009). The modifications common in genetic engineering are often described by synthetic biologists in this manner as one-off and bespoke. Smolke (2009) makes the same distinction in a slightly different manner by stressing the role of engineering principles in synthetic biology: 'It is the focus on the development of new engineering principles and formalism for the substrate of biology that sets it apart from the more mature fields upon which it builds, such as genetic engineering' (p.1073). The idea that biology is a new substrate for engineering is one that is echoed by other synthetic biologists. One founder of the BioBricks approach explained that the application of engineering to biology was inevitable, because biology was one of the few remaining available substrates that was yet to be engineered (Synthetic biologist 9).

We should perhaps not be too hasty to accept the idea that synthetic biology is a new approach to the engineering of biology, however. The historian Luis Campos (2009) points out that an engineering approach to life can be found at least as far back as the late 19th century when some biologists started to think of themselves as engineers. He gives examples such as Loeb's book *The Mechanistic Conception of Life*, published in 1912, and Jacob and Monod's work in the 1960s which talked about how genetic circuits could be engineered. But Campos also observes 'a peculiar perception common among synthetic practitioners, and recurring over decades: that they alone have been the first to truly aim for – and possibly attain unto – a properly engineered biology' (p.16). His argument is that we are seeing history repeating itself in the case of synthetic biology.

Engineering

Having provided some background, I now turn to the nature of engineering knowledge, which is often discussed at synthetic biology meetings in terms of the contrast between science and engineering. At these meetings we regularly hear aphorisms such as ‘A scientist builds in order to learn, an engineer learns in order to build’ (Fred Brooks quoted in Nightingale 2004). This distinction is reminiscent of the famous Marxist quotation: ‘the philosophers have only interpreted the world in various ways. The point however is to change it’ (Marx 1992). Campos (2009) also connects this famous phrase with the engineering mentality by calling this desire to change the world a ‘Marxist-cum-engineering philosophy’ (p.14). This is not to imply that all engineers are Marxists (in fact Noble 1977 has argued that engineers are domesticated servants of capital). But even without the Marxist connotations, the point is that an important objective in engineering is to make the world a better place. And this desire is shown in the tag line: ‘making life better, one part at a time’ which is found at the bottom of every page of the www.syntheticbiology.org website.

The aspiration to change the world for the better is widely found in the discussion of engineering. Vincenti (1990), in his work on the nature of engineering knowledge, says that ‘Engineering refers to the practice of organizing the design and construction of any artifice which transforms the physical world around us to meet some recognized need’ (p.6). In this sense, engineering is, by definition, instrumental. Knowledge is a means to a certain end, not an end in itself for engineers. Vincenti even says that ‘Engineering can, in fact, be defined in terms of these ends’ (p.6). This mentality produces a focus on problem-solving, which Downey (2009) argues is pervasive among engineers more generally. He notes that ‘Many times I have watched engineers, including myself…endeavor to transform situations of work and life into definable problems to solve’ (p.59). What is particularly interesting from an STS perspective, is that because of the needs-driven, problem-oriented emphasis of engineering, it becomes a *social* activity which ‘is intimately bound up with economic, military, social, personal, and environmental needs’ (Vincenti 1990: 11).

When considering the differences between science and engineering, it is tempting to set up a dichotomy, with science on one side, driven by discovery, understanding and the desire for comprehension, and engineering on the other, motivated by the aim to create, construct and design. Here it is the *intentions* that are different between science and engineering. And it is the case that some synthetic biologists do talk about how they simply want to make things; how they want to use biology to construct and to build (Synthetic biologist 9; Synthetic biologist 14). Some commentators set up the science/engineering distinction in this manner as understanding/making (or we could perhaps say head/hand) and conclude that this is why the philosophy of engineering has received much less attention than the philosophy of science (McCarthy 2006). If engineering is not concerned with the acquisition of knowledge but with changing the world, it does not fit easily into an epistemological framing (McCarthy 2006).[4]
But further investigation shows that this dichotomy is over-simplified. There are many synthetic biologists who think that the most important objective of synthetic biology is to increase understanding. Benner and Sismour (2005) say, for example, that one of the measures of success of synthetic biology will be how well the creation of artificial systems ‘drives new discoveries and new theories’ (p.534).

When there is talk of *understanding* in synthetic biology, synthetic biologists often reach for the quotation from the physicist Richard Feynman 'what I cannot create I do not understand', which was found written on his blackboard when he died in 1988. This quotation has become the 'motto' of synthetic biology, because it brings together the two aspirations of biology (understanding) and engineering (creation).[5] In this sense synthetic biology is not just about creating new things, because creating new things also helps us understand existing ones better.

Despite these concessions to the importance of understanding in synthetic biology, however, there is a strong rhetoric among synthetic biologists that biology on its own is unsatisfactory, and needs to be transformed into an engineering discipline. Arguments are made that the successes of engineering are obvious, and demonstrated by artefacts such as planes, bridges, computer processors etc., which, it is claimed, are 'made possible by sophisticated engineering programs that model characterized parts that are designed and manufactured to work together predictably' (Arkin 2008). This leads synthetic biologists to the conclusion that 'it is economically and socially important that we improve the efficiency, reliability and predictability of our biological designs' (Arkin 2008: 774). As this quotation makes explicit, again we see the appeal to social need.

But is there something else beyond (apparent) social need behind these aspirations? We may also be seeing here is a desire to make the world more instrumentalizable, manipulable and controllable. This, again, is central to engineering in other fields, as previous studies have shown. For example, Florman (1976) says 'every engineer has experienced the comfort that comes with total absorption in a mechanical environment. The world becomes reduced and manageable, controlled and unchaotic' (p. 137).[6] Kleif and Faulkner (2003) in their work on robot builders and software engineers also maintain that one of the most important things about engineering is that it becomes possible to overcome uncertainty and ambiguity: 'Although uncertainty is immanent in engineering, there is also a strong faith in the possibility of overcoming it. And this is a big part of the pleasure in technology' (p.311).

This kind of talk is widely found in synthetic biology. For example, it is common to hear statements such as: 'Fatty acid regulation is known and can be overcome' (Synthetic biologist 11). Here the idea is that knowing something enables one to control it, and to 'overcome' it. There is also much discussion of 'controlling' aspects of biology, such as the central dogma and gene expression (Young and Alper 2010). And Weiss (2009) writes about how synthetic biologists 'strive to design and control complex intracellular and extracellular activities that allow us to achieve precisely defined engineering or scientific goals' (p.1073). Here we clearly see the aspiration to make the biological world manageable and controllable.

Another key feature of the engineering approach to synthetic biology is the attempt to reduce biological complexity. For example, Tom Knight summarises the engineer's attitude to complexity: 'a biologist is delighted with complexity. The engineer's response is: 'How can I get rid of this?''. Another synthetic biologist George Church similarly explains that 'You focus on parts of the science that you do understand and clean out the parts that you don't understand' (Breithaupt 2006: 22-3). In a broader sense, we could interpret these aspirations to reduce complexity as 'relentlessly pursuing the program of making every element of the world programmable or susceptible to engineering' (Pottage 2007: 340). But the point I want to make here is that it is not a criticism of engineering to say that it is instrumental, and that it aspires to prediction, control and the reduction of complexity, because the whole point of engineering is to put scientific knowledge to practical uses. By making biology into engineering, the instrumentalism becomes an unquestionable part of the field; it is part of the definition of engineering.

Adopting an engineering perspective on living things is, however, an immediately provocative stance, if one thinks that that engineering biology is qualitatively different from engineering other materials (Preston 2008). A related point is that throughout history, scientists who have taken an engineering approach to life (like Leduc and Loeb) have been accused of not doing *real* biology (Campos 2009). Lazebnik (2002) thinks this can be explained by the view held by some that 'engineering approaches are not applicable to cells because these little wonders are fundamentally different from objects studied by engineers' he goes on to say that 'What is so special about cells is not usually specified, but it is implied that *real biologists feel the difference*' (p.181, emphasis added). The issue of whether synthetic biologists are 'real biologists' and whether synthetic biology is itself 'real biology' is a fascinating one, which is likely to resurface often as the field develops. Keller (2009) argues that synthetic biology should not be called 'biology', because the guiding aim of synthetic biology is not to find out about the natural world. But from an engineering perspective it may not be a criticism of synthetic biology to say that it is not real biology. Engineers want to make biology do things for them (and for us), and this instrumental perspective defines their approach.

Engineering analogies and engineering principles

In order to align itself with engineering, synthetic biology makes heavy but rather indiscriminate use of engineering analogies. For example, the word 'chassis' is borrowed from mechanical engineering to describe the cellular context into which biological parts can be put. There is talk of 'refactoring' bacteriophage – a term borrowed from software engineering (Chan et al. 2005). There is also much discussion of how DNA, RNA and proteins behave like transistors, resistors and capacitors in electrical circuits (Andrianantoandro et al. 2006). The recurrence of analogies from electronic engineering explains the search for oscillators in biology, a search which resulted in the landmark 'repressillator' paper (Elowitz and Leibler 2000). A repressillator is a rather unstable biological oscillator, and could be described as a true example of hybridicity between biology and engineering. In short, we see a broad mixture of engineering analogies being drawn on in synthetic biology from mechanical, electrical and software engineering.

Engineering principles are also often applied to synthetic biology, and this is perhaps one of the clearest ways in which synthetic biology is becoming described in terms of engineering. For example, there are many attempts in synthetic biology to develop components which are modular and can be combined in a 'plug and play' manner (Isaacs and Collins 2005). This requires that biological parts are standardized, so that new parts do not have to be created in a bespoke manner each time they are required (Arkin 2008). Other engineering principles that are said to be key to synthetic biology are abstraction and decoupling (Endy 2005). I focus on two engineering principles here: modularity and decoupling.

Modularity in synthetic biology
One of the most important of the engineering principles is modularity. Agapakis and Silver (2009) explain that 'A system can be described as modular if its components can be functionally separated and recombined' (p.704), i.e. if the constituent elements retain their properties irrespective of their context, like Lego bricks. They say that it is possible to observe modularity in biology at the level of nucleic acids, proteins and pathways.

There is much discussion over what constitutes a module in a biological context, however. The Mitchell (2005) asks the key question: 'Is nature modular, or do we impose modularity on it in order to understand it?' (p.101). She adds the warning that 'Since our accounts of nature always carry along a conceptual framework, it is impossible to give a definitive proof that what we describe (modularity) is really in the world' (p.101). The pervasiveness of the conceptual framework that we carry along with us can be found in some scientific papers that describe perceived modularity in biology. For example, some find it 'wondrous that the solutions found by evolution have much in common with good engineering' (Alon cited in Lynch 2007: 803). But others maintain that 'it remains unclear whether modules really exist or whether they are simply a construction used to disentangle complex biological networks' (Morange 2009: S50-S51). This issue is the subject of much discussion in the scientific literature. Some think that it is clear that evolution has selected for modularity because it enables different parts of the system to evolve independently (Sauro 2008), while others disagree (Lynch, 2007). Morange (2010) interestingly suggests that one of the things that synthetic biology can do in respect to modularity is to 'explode a poorly defined category' (p.375), by seeing if synthetic modular entities can be made to function in a range of different biological circumstances.

Further analysis shows that modularity is not a straightforward concept even in more conventional forms of engineering. In electronics, for example, something that is downstream to an apparently modular entity, such as a capacitor, can interfere with this entity in a phenomenon called retroactivity (Del Vecchio et al. 2008). Furthermore, electronic components are not identical to one another, and in some circumstances they can betray their idiosyncrasies (Thompson 1997). To add an extra twist, artificial evolution and genetic algorithms can be used to help design more efficient electronic circuits (Thompson 1997). It could perhaps be argued that we see an idealisation of electrical engineering in synthetic biology, and that when we look closer, we see that electronic circuits do not behave in a completely predictable and modular manner like Lego bricks.

And even the analogy with Lego bricks can be challenged. Their power as an analogy is based on the idea that they fit together in a predictable manner irrespective of context. However, more advanced Lego toys do not use standardized, interchangeable parts, but are made up of specialised pieces designed for particular creations, such as Hogwarts Castle in the Harry Potter collection.[7] Similar types of bespoke, specially engineered parts are used in other industries, such as in the construction of spacecraft (Richards 2008).

Although we can challenge the analogies to modularity in engineering, this does not stem the enthusiasm among synthetic biologists to try to create modularity in biological systems. One of the attractions of modularity is that it enables expertise and labour to be distributed, as can be seen in the case of the personal computer, where video cards, for example, can be designed completely separately from motherboards (Langlois 2010). Such division of labour enables mass-production. Modular systems are also particularly well suited to open source ownership regimes (see Calvert 2008). Importantly, modularity enables some biological features to be ‘black boxed’. In other words, if biological parts behave in a predictable manner whatever their context, then they do not have to be fully understood by the researcher who is working on them. If biology can be successfully black-boxed, not everyone working on synthetic biology needs to have skills in molecular biology. This enables synthetic biology to become more easily accessible.

One of the consequences of this deskilling has been the rise of ‘Do It Yourself’ biology, sometimes called ‘citizen science’ or ‘amateur science’. This is a loose global collective which is made up of a mixture of people most of whom are ‘biocurious’ amateurs (approximately 95%), with the remainder being artists, ‘moonlighting’ working scientists, and bioentrepreneurs (Cowell 2010). DIYbio is a worldwide phenomenon, with groups in the Bangalore, Indonesia and Singapore as well as in the US and Europe.[8] It can be seen as one example of a broader trend towards greater participation in science and technology, alongside patient advocacy groups, direct-to-consumer genetic testing, and open source programming (see Kelty 2010). DIYbio, being non-institutional science, is not part of synthetic biology strictly speaking, but it is inspired the aim to modularize and standardize biological entities and techniques that we find in synthetic biology.

Decoupling and design

Aside from modularity, the second engineering principle that is of particular relevance here is decoupling. In engineering, decoupling is the idea that there is a separation between the processes of design and fabrication (Endy 2005). We see this in the construction industry where a building is designed by an architect and built by a structural engineer. Decoupling in synthetic biology is enabled by gene synthesis technologies, which allow DNA sequences to be designed according to the requirements of synthetic biologists. We see this freedom to design in the names of the software used in synthetic biology, such as ‘Gene Designer 2.0’ (Mackenzie 2010).

The ability to design, enabled by decoupling, is perhaps an inevitable consequence of synthetic biology becoming an engineering discipline, because there are close links between engineering and design. Antonsson (1987) argues that ‘It is design, or the synthesis of useful devices, which distinguishes engineering from science. In fact *design* is the very essence of engineering’ (p.1 emphasis in original). And Turnbull (2007) agrees that ‘While engineers engage in a wide range of activities it is design that lies at the core of the discipline’ (p.2). Simon’s (1969) definition of design as ‘the transformation of existing conditions into preferred ones’ (p.55), shows that design is continuous with the ameliorative impulse that drives engineering.

In the context of synthetic biology, the hope is that decoupling will free living systems from the constraints of evolution, making nature something that can be designed. Some synthetic biologists argue that nature’s canvas is limited by the contingencies and path dependencies of evolution, and with our technical powers and imagination we can enlarge that canvas (Bedau and Parke 2009). As Fritz et al. (2010)

put it: ‘the drive to look beyond what does exist to what can exist is ushering in an era of biology by design’ (p.1). The aspiration is that biology will become a product of design choices, rather than evolutionary pressures (Allenby 2007). These design choices can include industrial and political imperatives, such as security issues, and even aesthetics. What decoupling does in this way is enable social concerns to be designed into synthetic biological products (Mackenzie 2010). Importantly, the inescapably ‘value-laden character of design’ (Johnson and Wetmore 2007: 570), means that when something is designed this necessarily opens up a whole host of further questions such as: is it designed well or not? For what purpose is it designed? And who is it designed for? (Latour 2008). By making biology into something that can be designed, synthetic biology opens biology up to broader discussion.

A new kind of engineering?

I have explored the engineering principles that are applied to synthetic biology, focusing particularly on modularity and decoupling. But it should be acknowledged that some scientists working in synthetic biology think that it is inappropriate to apply engineering analogies and principles to biological systems. For example, de Lorenzo and Danchin (2008) think that there is an ‘overly simplistic projection of electronic engineering concepts into supposedly biological counterparts’ (p.824). Some maintain that the emergent properties that define living things militate against their successful modularisation (see Calvert 2008). Others argue that the whole engineering project might fail, because of the unpredictable, complex, noisy and context-dependent nature of biological systems (Kwok 2010).

Even amongst those who are keen to promote the engineering agenda, there is an increasing recognition that engineering in biology may look rather different from engineering in other areas. Some have suggested that perhaps we will have to think about changing our understanding of engineering when we apply it to biology. This point is made by Weiss (2009):

> ‘we must also be cognizant of the interesting and challenging features of the biological substrate that make it different from all other existing engineering disciplines (e.g., self-replication, self-repair, mutation and evolution, high degree of noise, incomplete information and the importance of cellular context)’ (p.1073).

In recent years there has been much discussion among synthetic biologists of the ‘interesting and challenging features of the biological substrate’, particularly complexity, noise and evolution (Purnick and Weiss 2009). And there is increasing recognition that although human-made engineered systems work by using insulation and isolation of parts, this may not be what we find in nature, because of the ‘radical interconnectedness of cellular context’ (Andrianantandro et al. 2006: 13). The conclusion that is usually drawn from these observations is not that synthetic biologists should give up on their attempts to engineer biology, but that they should use these particular features of biology to develop new ways of doing engineering (see Fritz et al. 2010).

As synthetic biologists often point out, there are many ways in which biological systems are superior to engineered systems. For example, biological systems are extremely robust (Kitano 2007), they exhibit exquisite sensitivity and specificity (demonstrated by the sensitivity of the olfactory system), and they can use sunlight as an energy source (Smolke and Silver 2011). They are also good at CO_2 capture and can synthesize complex molecules using multi-step enzymatic processes (Elfick 2011). Furthermore, evolution and reproduction are powerful techniques that many synthetic biologists would like to harness to their own ends (Synthetic biologist 9).

Engineer or tinkerer?
If synthetic biologists do develop a new type of engineering in this manner, to what extent will we legitimately be able to call this activity engineering? How far can the idea of engineering be stretched? It is interesting to look at arguments made by François Jacob in the 1970s in this light. Jacob (1977) criticises the idea that evolution can be thought of as an engineer. He says that we should think of living things instead as the product of 'a tinkerer who uses everything at his disposal to produce some kind of workable object' (p.1163). Jacob develops this idea of tinkering by drawing inspiration from Levi Strauss' (1966) discussion of 'bricolage'. O'Malley (2010) similarly describes the rather haphazard character of much synthetic biology by using the notion of 'kludging', and a term with related resonance which is widely used in the synthetic biology community is that of 'hacking'.[9] These may all be more appropriate ways of understanding synthetic biology than of thinking of it as some form of rational engineering.

The DIYbio movement explicitly embraces the playful, tinkering nature of their activities, and are happy referring to themselves as 'hackers' (Guthrie 2009). They use a definition of tinkering from the San Francisco Exploratorium – a definition which resonates with Jacob's – to describe their activities:

> 'It's about figuring out how things work and reworking them. Contraptions, machines, wildly mismatched objects working in harmony – this is the stuff of tinkering. Tinkering is, at its most basic, a process that marries play and inquiry'.[10]

A focus on tinkering highlights the playful and experimental character of synthetic biology, and this could be interpreted as somewhat diluting the aspirations for mastery and control that we find in engineering (Helsten and Nerlich 2011). But tinkering becomes problematic in a context where industrialisation, up-scaling and mass production are the goals, as they are in synthetic biology and in engineering more generally.

There may be more continuities between tinkering and engineering than are first apparent, however. Kleif and Faulker (2003) point out that engineers have an exhilaration about what technologies can do, and that fun is an important element of pleasure in engineering. And Morange argues that engineers are actually often opportunistic and are likely to use whatever is easily available, meaning that 'The sharp and illuminating distinction between engineers and tinkerers holds only as far as one has an ideal view of the behavior of engineers' (p.371). This view is also found in a recent editorial by four leading synthetic biologists, who argue that 'rather than separating science from engineering…the new questions posed by the early 'tinkerers' have created and amplified opportunities at the intersections of chemistry, physics, biology and engineering' (Collins et al. 2010: 1). If we give up on an idealised understanding of rational engineering we can perhaps get a better grip of interdisciplinary activities that go on under the heading of synthetic biology, where we regularly see crossovers and 'mash-ups' between people coming from different science and engineering traditions, who often retrain and reinterpret their work, as well as their professional identities.

We should also be wary of treating engineering itself as homogenous, because there are many different types of engineer. Synthetic biology attracts engineers trained in chemical engineering, control engineering, electrical engineering and mechanical engineering, to name a but few. These subfields have different approaches and assumptions. Control engineers, for example, may be much more familiar with dealing with robustness and systems theory than mechanical or computational engineers (Stelling et al. 2004). We will perhaps see a new type of engineer/biologist emerging who will be particularly well-suited to working with the contingencies and unpredictabilities of the biological substrate.[11]

Heterogeneous engineers

There will have to be mechanisms to support this new type of engineer/biologist, and the proponents of the BioBricks approach realise that it is necessary to train a new cadre of engineers who will specialise in synthetic biology. One of the mechanisms of doing this has been to set up an undergraduate competition called the International Genetically Engineered Machines competition (iGEM). This annual event started at MIT in 2003, and it has grown exponentially since, with the 2012 competition hosting 191 teams from all over the world, including 55 teams from Asia.[12]

iGEM has similarities with 'Do It Yourself' biology, in fact, Endy (2010) has dubbed iGEM 'Do It Together' biology. As with the DIYbio phenomenon, the iGEM competition broadens synthetic biology to a wider range of participants than would normally participate in a cutting-edge scientific field, to include teams of undergraduates and in some cases even high school students. Another similarity to DIYbio is that in iGEM there is the idea that applying engineering to biology is fun and 'cool' (Goodman 2008).

A feature of iGEM that is particularly interesting from a social scientific perspective is that there is an aim to build a community that not only possesses certain technical skills and approaches, but that shares certain values about safety, security and open access to the technology. The students are rewarded for integrating these aspects into their scientific projects, so they are being encouraged to think about the social and the technical dimensions of their work simultaneously.

What we see exhibited particularly well in the iGEM competition is a demonstration of synthetic biologists not just behaving as engineers, but behaving as *heterogeneous engineers*. This is a concept first used by Law (1987) to draw attention to the fact that engineers must incorporate social, political, economic and human factors into their technical work (Hamlin 1992). The concept was developed on the basis of the observation that engineers do not simply produce technological devices, but that 'Airplanes, electric power plants, the Internet, refrigerators, and playpens are complexes of artifacts together with social arrangements, social practices, social relationships, meanings, and institutions' (Johnson and Wetmore 2007: 575).

As well as mobilizing social, political and institutional components, heterogeneous engineers also contribute to the building of society (Johnson and Wetmore 2007). Winner (1986) has famously shown how machines and other artifacts 'can embody specific forms of power and authority' (p.19), and can in this manner engineer relationships among people. In this sense 'The things we call 'technologies' are ways of building order in our world' (p.28). So we not only see synthetic biologists redesigning nature to fit the engineering ideal, but also redesigning society. For this reason, Law and Callon (1988) argue that engineers are 'engineer-sociologists' (p.284); 'social activists who design societies or social institutions to fit those machines' (p.284). This bringing together of technical and political forces is particularly apparent in synthetic biology. And the widespread integration of 'ethical, legal and social issues' (or 'Human Practices') into synthetic biology is a demonstration that social scientists are one of the components being mobilised by these heterogeneous engineers (Calvert and Martin 2009).

Conclusions

As the discussion of the nature of engineering knowledge showed above, the engineering impulse is ameliorative; the objective is to improve the world. However, the understanding of what constitutes a 'better' world is confined by the instrumental engineering imagination, where the aim is to make the world more manipulable and controllable, where every situation is interpreted as a problem to solve, and where ends are more important than means. As Law and Mol (2002) make clear, this perspective 'misses those places that don't fit so well with the control impulse' (p.137). In nanotechnology we see the 'engineer's perspective on human minds and bodies as more or less well-designed technical products' (Nordmann 2007: 42), and we should not be surprised if this is how engineers interpret the biological world. If engineers are the dominant voice in the synthetic biology of the future then we may expect to see the growth of a certain type of synthetic biology aligned with the engineering agenda.

What I have argued here, however, is that there is another side to the engineering agenda. Both engineering and design are activities that incorporate broader social goals and values. And heterogeneous engineers incorporate non-technical components into their thinking and practices. By making biology into an engineering discipline, synthetic biologists are simultaneously broadening the range of voices that can enter into the discussion of their field. The boundaries surrounding biotechnology are becoming more permeable, and this is opening up synthetic biology to a diverse range of global groups. Since 'making life better' means different things to different people, the involvement of such new communities in synthetic biology could help expand and challenge dominant ways of imagining how we should make use of our increased powers to manipulate the biological world.

[1] www.syntheticbiology.org
[2] Based on four interviews with protocell synthetic biologists.
[3] This is a paraphrase of a joke from the comedian Simon Munnery.
[4] Philosophers of science also often assume that the science/engineering distinction is the same as the science/technology distinction. But Davis (1996) argues that 'engineering equals technology' is a mistake (p.98), because the history of engineering is not the same as the history of technology. Although the output of engineering may be technologies, engineering itself is an approach and a profession.
[5] An incorrect version of this quotation ('what I cannot build, I cannot understand') was coded into the bacteria *Mycoplasma mycoides* JCVI-syn1.0 (Gibson 2010) – another demonstration of its centrality in the field of synthetic biology.
[6] Quoted in Kleif and Faulkner (2003: 307).
[7] There are also examples of synthetic biologists moving away from Lego analogies. Endy has recently stated that 'We now need to move beyond Lego metaphors and genetic toys to professional technologies' (quoted in Sanders 2010).
[8] See diybio.org/ and http://diybiosingapore.wordpress.com/
[9] Synthetic biology company Ginkgo Bioworks' phone number is +1877 HACK DNA.
[10] http://tinkering.exploratorium.edu/
[11] Different substrates, aside from biology, also lead to differences *within* engineering. As Arkin (2008) says in respect to standardization: 'Some engineering fields have more formal and less mutable standards than others owing to the nature of their substrate and the uncertainties that plague their manufacture and deployment' (p.744).
[12] See http://ung.igem.org/Team_List?year=2012

References

Agapakis, C.M. and Silver, P.A. (2009), 'Synthetic biology: exploring and exploiting genetic modularity through the design of novel biological networks', Molecular BioSystems, 5, pp.704–713.

Allenby, B. (2007), 'From human to transhuman: technology and the reconstruction of the world', Templeton Research Lecture, Arizona State University, 22 October 2007.

Andrianantoandro E., Basu S., Karig D.K., and Weiss, R. (2006), 'Synthetic biology: new engineering rules for an emerging discipline', Molecular Systems Biology, Article number: 2006.0028, doi: 10.1038/ msb4100073.

Antonsson, E.K. (1987), 'Development and testing of hypotheses in engineering design research', ASME Journal of Mechanisms, Transmissions and Automation in Design, 109(2), pp.153-4.

Arkin, A. (2008), 'Setting the standard in synthetic biology', Nature Biotechnology, 26(7), pp.771-4.

Bedau, M.A. and Parke, E.C. (2009), 'Introduction to the ethics of protocells' in M.A. Bedau and Parke, E.C. eds, The Ethics of Protocells: moral and social implications of creating life in the laboratory. Cambridge, MA: MIT Press.

Brent, R. (2004), 'A partnership between biology and engineering', Nature Biotechnology, 22(10), pp.1211-1214.

Benner, S.A. and Sismour, A.M. (2005), 'Synthetic biology', Nature Reviews Genetics, 6, pp.533-543.

Breithaupt H. (2006), 'The engineer's approach to biology', EMBO Reports, 7(1), pp.21-24.

Calvert, J. (2008), 'The commodification of emergence: systems biology, synthetic biology and intellectual property', BioSocieties 3(4), pp.385-400.

Calvert, J. and Martin, P. (2009), 'The role of social scientists in synthetic biology', EMBO reports, 10(3), pp.201-204.

Campos, L. (2009), 'That was the synthetic biology that was', in M. Schmidt, Kelle A., Ganguli-Mitra A. and de Vriend H. eds, Synthetic Biology: The technoscience and its societal consequences. Heidelberg: Springer, pp.5-21.

Chan L.Y., Kosuri S., Endy, D. (2005), 'Refactoring bacteriophage T7', Molecular Systems Biology, Article number: 2005.0018, doi: 10.1038/msb4100025.

Collins, J.J., Endy, D., Hutchison, C.A. and Roberts, R.J. (2010), 'Editorial: synthetic biology' Nucleic Acids Research, 38(8), pp.2513.

Cowell, M. (2010), 'DIYbio: let's play with biotechnology', talk at the University of Edinburgh, 26th March 2010.

Davis, M. (1996), 'Defining 'engineer': how to do it and why it matters', Journal of Engineering Education, 85(2), pp.97-101.

de Lorenzo, V. and Danchin, A. (2008), 'Synthetic biology: discovering new worlds and new words', EMBO reports, 9(9), pp.822-827.

de Vriend, H. (2006), Constructing Life. Early social reflections on the emerging field of synthetic biology. The Hague: Rathenau Institute

Del Vecchio D., Ninfa A.J., and Sontag E.D. (2008), Modular cell biology: retroactivity and insulation. Molecular Systems Biology 4: Article number 161 doi:10.1038/msb4100204

Downey, G.L. (2009), 'What is engineering studies for? Dominant practices and scalable scholarship', Engineering Studies, 1(1), pp.55-76.

Elfick, A. (2009), 'What exactly is synthetic biology?', online at http://www.synbiostandards.co.uk/about_synbio.php [accessed 11 May, 2013]

Elfick, A. (2011), ‘Standardisation in Synthetic Biology’, talk at the Synthetic Biology Student Symposium, University of Glasgow, 4th April 2011.
Elowitz, M.B. and Leibler, S. (2000), ‘A synthetic oscillatory network of transcriptional regulators’, Nature, 403, pp.335-338.
Endy, D. (2005), Foundations for engineering biology. Nature, 438 (24 November 2005), pp.449-453.
Endy, D. (2010), ‘Overview and Context of the Science and Technol of Synthetic Biology’, Presentation to the Presidential Commission for the Study of Bioethical Issues, 8th July 2010.
Florman, S. (1976), The existential pleasures of engineering. New York: St. Martin's.
Fritz, B.R., Timmerman, L.E., Daringer, L.M., Leonard, J.M. and Jewett, M.C. (2010), ‘Biology by Design: From Top to Bottom and Back’, Journal of Biomedicine and Biotechnology, Volume 2010, Article ID 232016, doi:10.1155/2010/232016.
Gibson, D.G. et al. (2010), ‘Creation of a bacterial cell controlled by a chemically synthesized genome’, Science, 329(5987), pp.52-56.
Goodman, C. (2008), ‘Engineering ingenuity at iGEM’, Nature Chemical Biology, 4(1), p.13.
Guthrie, J. (2009), ‘Do-it-yourself biology grows with technology’, San Francisco Chronicle, December 20th 2009, online at http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2009/12/20/MNFT1B1899.DTL [accessed 11 May, 2013]
Hamlin, C. (1992), ‘Reflexivity in Technology Studies: Toward a Technology of Technology (and Science)?’, Social Studies of Science, 22, pp.511-544.
Isaacs, F.J. and Collins, J.J. (2005), ‘Plug and play with RNA’, Nature Biotechnology, 23(3), pp.306-307.
Jacob, F. (1977), ‘Evolution and Tinkering’, Science, 196(4295), pp.1161-1166.
Johnson, D. and Wetmore, J. (2007), ‘STS and Ethics: Implications for Engineering Ethics’, in E.J. Hackett, et al. eds, The Handbook of Science and Technology Studies, Third Edition. Cambridge, MA: MIT Press.
Keller, E.F. (2009), ‘What Does Synthetic Biology Have to Do with Biology?’, BioSocieties, 4, pp 291–302.
Kelty, C.M. (2010), Outlaw, hackers, victorian amateurs: diagnosing public participation in the life sciences today. Journal of Science Communication 9(01), C03.
Kitano, H. (2007), ‘Towards a theory of biological robustness’, Molecular Systems Biology, 3; Article number 137; doi:10.1038/msb4100179.
Kleif, T. & Faulkner, W. (2003), ‘‘I’m no athlete [but] I can make this thing dance!’ Men’s pleasures in technology’, Science, Technology & Human Values, 28(2), pp.296-325.
Kwok, R. (2010), ‘Five hard truths for synthetic biology’, Nature, 463, 12st January 2010, 288-290.
Langois, R. (2010), ‘Organising the electronic century’, Seminar at the University of Edinburgh, 17th June 2010.
Latour, B. (2008), ‘A cautious Prometheus? A few steps toward a philosophy of design’, Keynote lecture for the Networks of Design meeting of the Design History Society Falmouth, Cornwall, 3rd September 2008.
Law, J. (1987), Technology, closure and heterogeneous engineering: The case of the Portuguese expansion. In Bijker, W. E., Hughes, T. P., and Pinch, T. J. (eds.)

The Social Construction of Technological Systems, New Directions in the Sociology and History of Technology, MIT Press, Cambridge, Mass.
Law, J. and Callon, M. (1988), ‘Engineering and sociology in a military aircraft project’, Social Problems, 35, pp.284-297.
Law, J. and Mol, A. (2002), Complexities: social studies of knowledge practices. Duke University Press.
Lazebnik, Y. (2002), ‘Can a biologist fix a radio?—Or, what I learned while studying apoptosis’, Cancer Cell, 2, pp.179-182.
Levi Strauss, C. (1966), The Savage Mind. University of Chicago Press.
Lynch, M. (2007), ‘The evolution of genetic networks by non-adaptive processes’, Nature Reviews Genetics, 8, pp.803-813.
MacKenzie, A. (2010), ‘Design in synthetic biology’, BioSocieties, 5, pp.180-198.
Marcus, G.E. (1995), ‘Ethnography in/of the World System: The Emergence of Multi-Sited Ethnography’, Annual Review of Anthropology, 24, pp.95-117.
Marx, K. (1992), Early writings. Penguin Books: London.
McCarthy, N. (2006), ‘Philosophy in the making’, Ingenia, 26, p.47-51.
Mitchell, S. (2005), ‘Modularity: More than a Buzzword?’, Biological Theory, 1(1), pp.98-101.
Morange, M. (2009), ‘A new revolution? The place of systems biology and synthetic biology in the history of biology’, EMBO reports, 10, pp.S50-S53.
Hellsten, I. and Nerlich, B. (2011), ‘Synthetic biology: Building the language for a new science brick by metaphorical brick’, *New Genetics and Society* 30(4), pp.375-397.
Noble, D. (1977), America by Design: Science, Technology, and the Rise of Corporate Capitalism. New York: Alfred A. Knopf.
Nordmann, A. (2007), ‘If and then: a critique of speculative nanoethics’, Nanoethics, 1, pp.31-46.
O'Malley, M., Powell, A., Davies, J. and Calvert, J. (2008), 'Knowledge-making distinctions in synthetic biology', BioEssays, 30(1), pp.57-65.
O'Malley, M.A. (2010), ‘Making knowledge in synthetic biology: Design meets kludge’, Biological Theory, 4(4), pp.378-379.
Pottage, A. (2007), ‘The socio-legal implications of the new biotechnologies’, Annual Review of Law and Social Science, 3, pp.321-44.
Preston, C.J. (2008), ‘Synthetic Biology: Drawing a Line in Darwin’s Sand’, Environmental Values, 17, pp.23-39.
Purnick, P.E.M. and Weiss, R. (2009), ‘The second wave of synthetic biology: from modules to systems’, Nature Reviews Molecular Cell Biology, 10(6), pp.410-422.
Richards, G. (2008), ‘The final frontier’, Engineering & Technology, 3(11), pp.44-47.
Sanders, R. (2010), ‘NSF grant to launch world's first open-source genetic parts production facility’, UC Berkeley News Centre, Jan 20th, 2010, online at http://newscenter.berkeley.edu/2010/01/20/biofab_synthetic_biology/ [accessed 11 May, 2013]
Sauro, H.M. (2008), ‘Modularity Defined’, Molecular Systems Biology, 4, pp.166.
Simon, H. (1969), The Sciences of the Artificial. Cambridge, MA: MIT Press.
Smolke, C.D. (2009), ‘Building outside of the box: iGEM and the BioBricks Foundation’, Nature Biotechnology, 27(12), pp.1099-1102.
Smolke, C.D. and Silver, P.A. (2011), ‘Informing Biological Design by Integration of Systems and Synthetic Biology’, Cell, 144(6), pp.855-859.

Stelling, J., Sauer, U., Szallasi, Z., Doyle, F.J., and Doyle J. (2004), 'Robustness of Cellular Functions', Cell, 118, pp.675–685.
Thompson, A. (1997), 'An evolved circuit, intrinsic in silicon, entwined with physics', in T. Higuchi and Iwata, M. and Weixin, L. eds, Proceedings of the First International Conference on Evolvable Systems (ICES'96), Berlin: Springer-Verlag, pp.390-405.
Turnbull, J.N. (2007), 'The context and nature of engineering design', A Philosophy of Engineering Seminar: Systems Engineering and Engineering Design, London: Royal Academy of Engineering.
Vincenti, W.G. (1990), What Engineers Know and How They Know It. Baltimore: Johns Hopkins University Press.
Weiss, R. (2009), 'Synthetic Biology: What's in a name?', Nature Biotechnology, 27, pp.1071-1073.
Winner, L. (1986), The whale and the reactor: a search for limits in an age of high technology. Chicago: University of Chicago Press.
Young, E. and Alper, H. (2010), 'Synthetic Biology: Tools to Design, Build, and Optimize Cellular Processes', Journal of Biomedicine and Biotechnology, Volume 2010, Article ID 130781, doi:10.1155/2010/130781.